The Pierre Auger Observatory: Perspectives on ultra-high energy cosmic rays

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The Pierre Auger Observatory: Perspectives on Ultra-High Energy Cosmic Rays

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Abstract

The Pierre Auger Observatory for ultra-high energy cosmic rays is under construction in Argentina. The Observatory will consist when completed of 1600 water Čerenkov tanks and 24 fluorescence telescopes, organized in 4 sites, sampling ground particles and measuring fluorescence light induced by cosmic showers. The Surface Detector with more than 600 detector stations and the Fluorescence Detector with half of its telescopes have started steady data taking in the beginning of 2004. A large number of events above 10^{19} eV has been detected as well as good quality hybrid data from combined measurements with both Surface and Fluorescence detectors. The current status of the Pierre Auger Observatory, its performances and preliminary data will be presented.

1 Introduction

The Pierre Auger Observatory will study the Ultra-High Energy Cosmic Rays (UHECR) whose existence is one of the intriguing mysteries of Astroparticle Physics. Since about 30 years a few of these cosmic rays with energies greater than about 10^{20} eV have been observed [1, 2, 3]. Not only their energy but also their propagation seems to be difficult to explain with traditional astrophysics acceleration mechanisms and with currently known Physics laws governing the particle propagation in the Universe. Several violent phenomena such as Active Galactic Nuclei hosting massive black holes, Gamma Ray Bursts or rapidly rotating young neutron stars could be candidates for accelerating particles up to high energies. However, no evidence exists for the moment that these objects can accelerate particles, protons or other nuclei, up to high energies. Moreover, the current data of the UHECR is too scarce to correlate it with any known sources.

The hadron propagation at extreme energies is affected mainly by the pion production with the cosmologic microwave background. For protons this threshold is at 5×10^{19} eV yielding a quenching of the flux at extreme energies for uniformly distributed sources. Since the candidates for extreme energy cosmic accelerators are rare in our vicinity (below 50 Mpc), one would expect to observe this so called GZK (Greisen, Zatzepin, Kutzmin) feature. The AGASA data indicates that the cosmic ray spectrum continues at high energies while the HiRes data seems to confirm the GZK feature in the spectrum [2][3]. Without drastically more statistics at high energies it is currently difficult to draw any conclusions on the shape of the cosmic ray spectrum beyond 5×10^{19} eV.

The construction of the southern site of the Pierre Auger Observatory is currently in progress in Argentina, on the plateau of Pampa Amarilla (Mendoza) at 1400 m altitude. The observatory takes advantage of using two detection techniques: sampling of the ground particles and detection of the fluorescence light induced by cosmic ray showers in the atmosphere. Currently more than 600 Surface Detector stations, out of 1600 of the total array, are taking data. Two of the four fluorescence sites, each having 6 telescopes, are also in operation. The hybrid data obtained by the two detection methods will allow us to pin down systematic errors and cross calibrate the two different techniques. In the following, the Pierre Auger Observatory will be presented. Its performance and preliminary data will be discussed.

2 The Surface Detector of the Pierre Auger Observatory

The Surface Detector (SD) of the Pierre Auger Observatory is composed of 1600 water Čerenkov detectors extending over an area of 3000 km^2. The spacing between tanks is chosen to 1500 m yielding full efficiency for energies above 10^{19} eV. The general layout of the Surface Detector is shown in fig. 1. The four Fluorescence Detector (FD) sites are indicated on the sides of the array.

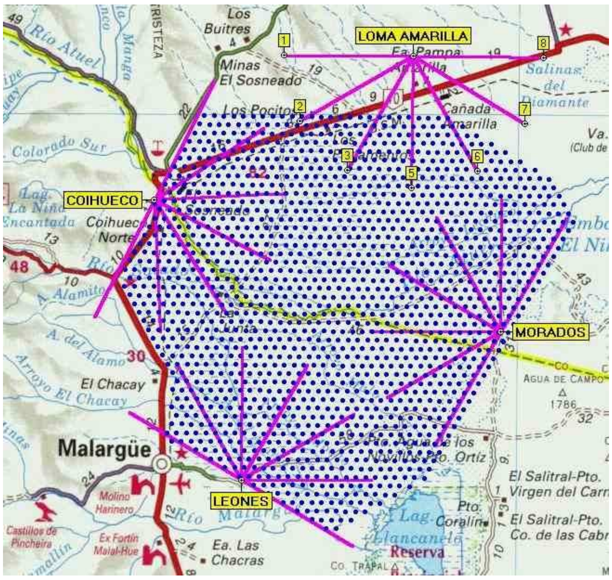

Figure 1: The layout of the Pierre Auger Observatory.

The detectors are cylindrical polyethylene tanks with 3.6 m diameter and 1.5 m height. The inside of the tank is covered by a Tyvek® liner for uniform reflection of the Čerenkov light, and the liner is filled with purified water up to a height of 1.2 m. The water is produced by a water plant at the observatory campus (Malargue) and its quality is about 15 MΩ.cm. Two solar panels combined with batteries furnish 10 W power for the station. Figure 2 presents a photo of a Surface Detector station.

The Čerenkov light from the water tanks is read out by three large photomultipliers (PMTs). The 9" XP1805 Photonis PMTs have been chosen for the production array. PMTs are equipped with a resistive base having two outputs: anode and amplified last dynode. This allows a large dynamic

Figure 2: Surface Detector Station.

range, total of 15 bits, extending from a few to about 10^5 photoelectrons. The high voltage is provided locally by a custom made ETL low power consumption (max 0.5 W) module. The nominal operating gain of the PMTs is 2×10^5 and can be extended to 10^6. The gain is determined in such a way that no saturation should occur for distances larger than 500 m from the shower core. The base, together with the HV module, is protected against humidity by Silicone potting.

The signals from anode and dynode are filtered with a 5 pole anti-aliasing filter with a cut-off at 20 MHz, and digitized at 40 MHz using 10 bit Flash Analog-Digital Converters (FADC). Two shower triggers are used: threshold trigger and time-over-threshold trigger. The first one is a simple majority trigger with a threshold at 3.2 VEM (Vertical Equivalent Muon) in each 4 or more tanks. The second one, time-over-threshold trigger requires 12 FADC bins with signals larger than 0.2 VEM in a sliding window of 3 μs in each of 3 or more tanks. The time-over-threshold trigger efficiently triggers on the shower particles far away from the shower core. In addition, a muon trigger allows for recording of continuous calibration data. The digital trigger circuitry is implemented with ACEX100 Programmable Logical Devices (PLD). A common time base is established for different detector stations by using the GPS system. Each tank is equipped with a commercial GPS receiver (Motorola OnCore UT) providing a one pulse per second output and software corrections. This signal is used to synchronize a 100 MHz clock which serves to timetag the trigger. Each detector station has an IBM 403

PowerPC micro-controller for local data acquisition, software trigger and detector monitoring, and memory for data storage. The station electronics is implemented on a single board, called the Unified Board, and packed in an aluminum enclosure. The electronics is mounted on top of the hatch cover of one of the PMTs and protected against rain and dust by an aluminum dome. In addition, each station has a Light Emitting Diode (LED) monitoring systems placed on a window on top of the liner, in the middle of the tank.

The individual detectors communicate with the base stations installed at the Fluorescence Detector sites through a 915 MHz wireless LAN. A 7 GHz microwave backbone network transfer data from the base stations to the Central Data Acquisition System (CDAS) at the observatory campus. The communication between the detector stations and the CDAS is bi-directional allowing a request for the full data readout in the case of a shower trigger, and for control of the detectors.

The Surface Detector "Engineering Array" (EA) consisting of 32 water tanks was in operation between 2001 and 2003 and allowed a test and validation of the detector concept. The production phase, with some minor changes and upgrades, started in 2003. A more detailed description of the Surface Detector can be found in ref. [4, 5, 6, 7, 8].

3 Surface Detector calibration and performances

The detector calibration is inferred from background muons. The typical rise time for a muon signal is about 15 ns with a decay time of the order of 70 ns. The average number of photoelectrons per muon collected by one PMT is 95. The measurement of the muon charge spectrum allows us to deduce the VEM value from which the calibration is inferred for the whole dynamic range. The cross calibration between the two channels, anode and dynode outputs, is performed by using small shower signals in the overlap region of the two channels. The linearity of the PMTs is controlled prior to the installation and the linearity of the whole electronics chain can be measured afterwards by using the LED system implemented in each tank. Additional information on calibration can be obtained from muon decay. The electron charge spectrum is peaked at about 15% of the muon charge and can be obtained from the calibration data.

The stable data taking with the SD started in January 2004 and various parameters are continuously monitored to ensure the array stability. The area/peak of the muon charge spectrum allows monitoring the electronics chain as well as the water quality. The mean value of the area/peak ratio for over 1000 PMT channels is 3.5 with an RMS of 0.2 showing good uniformity between differents detector stations. A slight temperature dependence of this value is observed, with a positive slope of $0.16\%/°C$. This is mainly due to the variation of the PMT gain as a function of temperature. It is noted that the temperature dependence does not affect the measurements since the data is continuously calibrated with background muons. The noise levels are very low. For both the anode and dynode channels, the mean value of the pedestal fluctuation RMS is below 0.5 FADC channels. The trigger rates are remarkably uniform over all detector stations, also implying good calibration and baseline determination. The threshold trigger rate is about 21 Hz with RMS 0.5 Hz and the time over threshold rate about 1.4 Hz with RMS 0.6 Hz.

The intrinsic resolution of the GPS time tagging system is about 8 ns requiring a good precision for the station location. An accuracy of one meter is obtained for the tank position by using the differential GPS method. The time resolution has been studied in the EA by comparing the time signals from two tanks, Carmen and Miranda, separated by 11 m. A Gaussian distribution with a 17 ns width was obtained. This resolution combines the dispersion due to arrival angles (15 ns) and the timing resolution of each tank and confirms the announced intrinsic time dispersion of about 8 ns. To perform an angle reconstruction, the starting points of the FADC traces need to be determined. This can be done with a resolution of about 7 ns due to the 25 ns FADC bins. Therefore, a total time resolution of $\sigma =$ 10 ns is achieved. This time resolution is sufficient to obtain a good angular resolution, around 1°, for the incoming primary cosmic rays.

4 The Fluorescence Detector of the Pierre Auger Observatory

The Fluorescence Detector (FD) is based on the measurement of fluorescence photons emitted from the shower during its development through the atmosphere. The shower particles, mostly electrons and positrons, excite the atmospheric nitrogen along their path. The nitrogen molecules emit isotropically fluorescence photons, with wavelengths between 300 to 400 nm. The fluorescence yield is very low, approximately 4 photons per metre of electron track, but can be measured with large area imaging telescopes during clear new- to half-moon nights. This yields a duty cycle for the FD which is about 10-15 %. The Pierre Auger Observatory has 24 telescopes arranged into 4 sites located at the perimeter of the Surface Detector (fig. 1). The FD sites are situated at locations which are slightly elevated with respect to the ground array. Each site houses 6 telescopes with a 30° x 30° field of view providing thus a 180° view towards the array centre from 1° to 31° above the horizon.

In the telescopes a spherical mirror of 3.4 m radius of curvature concentrates the fluorescence light on the pixellated camera placed on the mirror focal surface. The telescopes have Schmidt optics and the aperture of the system is defined by a circular diaphragm of 2.2 m diameter. An annular corrector ring made of UV transmitting lenses of appropriate aspherical shape, corrects for spherical aberrations keeping the spot size to the nominal 0.5°. A UV transmitting filter, selecting the fluorescence band between 300 and 400 nm, is placed on the diaphragm. The filter, made of commercial M-UG6 glass sheets, acts also as the bay window, protecting the telescope from the dust. The telescope mirror elements are of two different types, allowing for parallel production : either 49 hexagonal shaped glass mirrors or 36 rectangular shaped aluminum mirrors. In both aluminum and glass mirrors, the average reflectivity of the segments is about 90% between 300 and 400 nm.

The focal plane of the mirrors is instrumented with a camera arranged in 20 x 22 pixels. Each pixel, of approximate size of 1.5° to be compared with the 0.5° spot diameter, consists of a photomultiplier tube (Photonis XP3062) with a hexagonal shape photocathode complemented by light collectors. Since a given pixel maps a portion of the sky, a typical cosmic ray shower appears as a set of contiguous pixels on the focal surface. The signal "moves" from pixel to pixel, with typical duration ranging from few 100 ns to μs depending on the distance of the shower to the detector, and lasting for several tens of μs. A picture of one of the FD telescopes installed in the Los Leones building is shown in fig. 3.

Signals from the PMTs, operated at low gain, $5x10^4$, are sampled by a 10 MHz 12 bit FADC. The dynamic range is increased to 15 bit by sampling with a lower gain the signal sum of groups of 11 pixels in a column. The pixel first level trigger is provided by a digital running sum over the FADC samples, with a threshold which is constantly regulated in order to keep the the pixel rate constant, to about 100 Hz. The electronics provide an online measurement of the variance of each pixel, which is used to monitor detector performances. The second level trigger, which is hardware implemented, is based on the recognition of patterns of four triggered pixels, with topology and time coincidence consistent with a cosmic ray shower. The third level trigger is a software trigger based on a fast shower reconstruction algorithm,

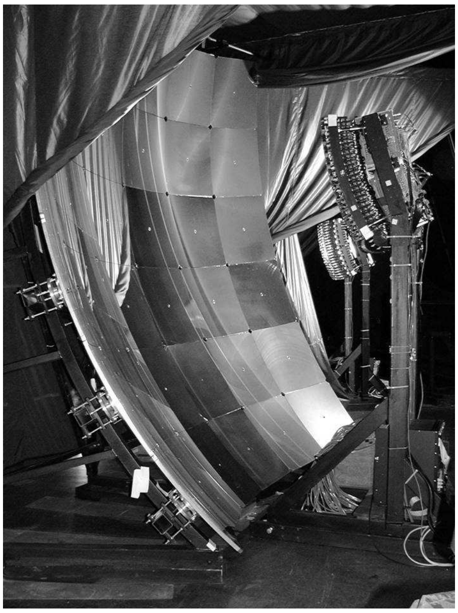

Figure 3: The FD telescope: on the left the spherical mirror with square shaped segments, on the right the PMT camera. The adjacent telescope's camera is also seen in the background.

which uses the second level trigger and FADC data. The second level trigger rate is a few tenths of Hz, which is reduced to less than 0.02 Hz by the third level trigger. The third level trigger algorithm provides a rough reconstruction of basic shower candidate parameters, like the time when the shower hit the ground, and the azimuthal position of the shower core at ground. These data are sent to the Central Data Acquisition System through the microwave link, and in case consistency with triggered SD tanks is found, an hybrid trigger is issued. Given the distances between the FD buildings, the standard data taking operation is done remotely from the Central Building. A more detailed description of the Fluorescence Detector can be found in ref. [4, 5, 6, 8, 9, 10].

4.1 The Fluorescence Detector calibration and atmospheric monitoring

The absolute calibration of the detector response is essential for the energy measurement with the FD. An end-to-end calibration of the telescopes is based on the uniform illumination of the camera pixels from a calibrated light source [11]. In addition to absolute calibration, a relative optical calibration system is used to monitor time variations in the telescopes calibration during the periods of data taking.

A precise determination of the fluorescence light emitted by the cosmic ray shower must take into account the attenuation of the light in its travel from the emission point to the detector. Both the standard Rayleigh scattering and the aerosol contribution have to be measured. Local atmospheric phenomena, like clouds, in the proximity of a shower can also significantly change the light pattern received by the detector. Seasonal variations of the pressure and temperature profile as a function of altitude can introduce systematic uncertainties in the reconstruction of the longitudinal shower development. A large variety of instruments with complementary characteristics in order to measure the scattering properties of the atmosphere and its time dependence has been developed [12].

Weather stations monitor the local air temperature and pressure and periodical balloon launches are performed in order to characterize the atmospheric pressure and temperature profiles. Each FD building is equipped with a wide angle infrared camera which monitors the cloud coverage in the telescopes field of view. The light attenuation in the atmosphere is measured by several independent methods. The Horizontal Attenuation Monitor measures the light extinction along a 45 km horizontal path between Coihueco and Los Leones, providing a measurement of the horizontal attenuation length at several wavelengths between 365 to 577 nm. The Central Laser Facility (CLF), located in the centre of the surface array, fires periodically a pulsed UV laser to vertical and inclined directions. The pulse travels through the atmosphere at the speed of light like the particles in a shower front. Instead of isotropic fluorescence emission, the FD telescope sees light that is Rayleigh scattered. Using the known Rayleigh differential scattering cross section, one can calculate the amount of light scattered toward the detector for any laser pulse energy, and compare it with the measured signal at the FD. Any difference can be attributed to the aerosol scattering, and its altitude profile can be measured.

A fully steerable LIDAR system is located close to each of the FD building. The system includes a frequency tripled Nd:Yag laser emitting pulses of 6 mJ energy and 4 ns duration at a wavelength of 355 nm, and an 80 cm diameter parabolic mirror focusing the back-scattered laser light onto a photomultiplier tube. LIDAR measurements are routinely performed during data taking. A triggering scheme which drives the LIDAR steering along the shower path when a shower is detected by the FD is being implemented, which will give detailed atmosphere information not on average basis but for each interesting event.

5 Preliminary data

Figure 4 shows two events triggered by the Surface Detector. The diameter of a circle is proportional to the logarithm of the particle density. The shower direction is obtained from a plane fit to the shower front determined from the particle arrival times. The primary cosmic ray energy is inferred from

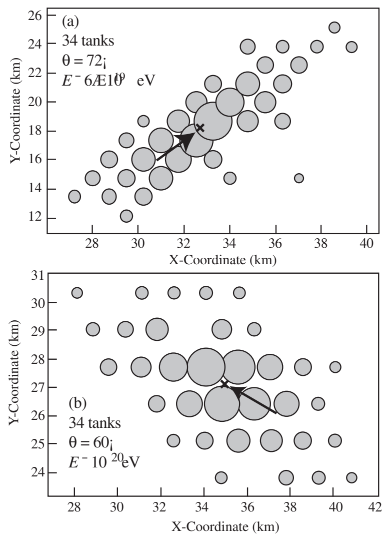

Figure 4: Example of two events detected by the Surface Detector.

the signal density at 1000 m from the shower core, S(1000). At energies considered by the Auger experiment, the shower fluctuations are small at 1000 m from the shower core giving a reliable estimate for the energy. The S(1000) is obtained from the lateral distribution function (LDF) representing the signal density as a function of the distance from the shower core. As an example, fig. 5 shows the LDF for the event in fig. 4b). The S(1000) is equal to about 65 VEM yielding a very preliminary estimate of the energy around 10^{20} eV.

The energy reconstruction calls for atmospheric shower simulations as well as for an accurate simulation of the detector response. Parameterizations for the S(1000) and the LDF function are currently being studied. The hybrid data will allow us to determine the most accurate energy estimators and systematic errors due to shower simulations.

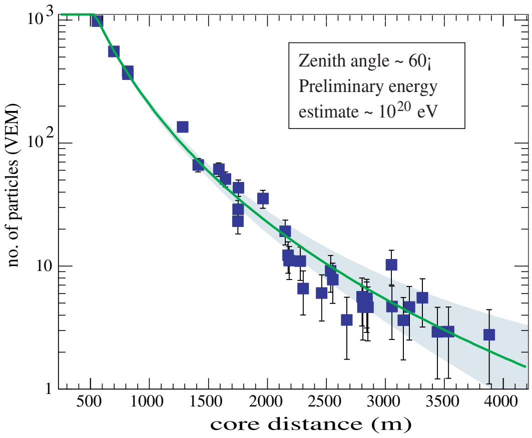

Figure 5: Lateral distribution function (see text). Only statistical errors are presented.

The discrimination of the primary composition can be inferred from the ground observables related to the age of the shower, hadronic heavy primaries yielding showers with larger muon content and earlier development. Several estimators for the primary identification are currently being studied: the muon tagging in the FADC traces, the analysis of the overall shape of the traces and the curvature of the shower front. The electronic parameters of the SD have been chosen to obtain sufficient discrimination power from FADC trace analysis. Figure 6 shows FADC traces for a rather inclined (right: 71°) and less inclined (left: 54°) showers. In the case of nearly vertical showers, the FADC traces extend over several microseconds at large distances from the shower core due to the electromagnetic component of the shower. In the case of inclined, old (non neutrino induced) showers, only the muon component remains, while the electromagnetic component has been absorbed by the atmosphere.

The discrimination of the muon and electromagnetic components will allow identification of neutrino induced, horizontal showers. These showers typically develop late in the atmosphere, or in the case of earth skimming tau neutrinos above the array, and would still have an electromagnetic component when detected by the array. This capability of nearly background free identification of neutrinos combined with the large acceptance of the tanks to horizontal showers provide a neutrino sensitivity which allows the testing of various AGN and top-down models [13].

In the case of the Fluorescence Detector data, the arrival direction of the primary cosmic ray is reconstructed from the pixel directions and sig-

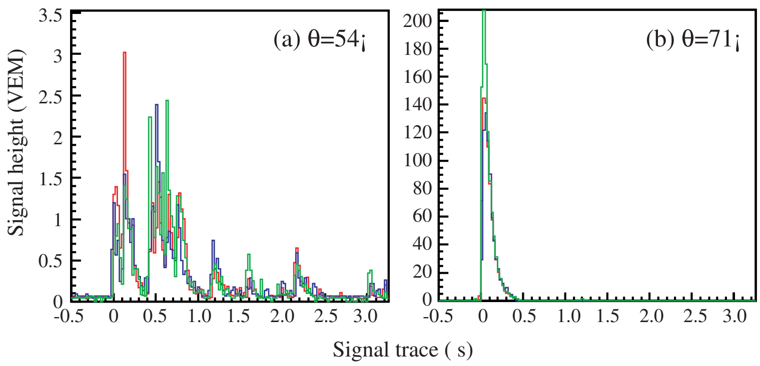

Figure 6: FADC traces recorded at about 800 m from the shower core. The different colors (grey-scales) represent the signals of the individual PMTs within a detector. The traces on the right corresponds to a more inclined shower having only the muon component left.

nal times. The energy measurement relies on the detection of fluorescence photons, which are proportional to the energy deposited by the shower particles in air. The measured signal is then corrected for the fluorescence light attenuation in the atmosphere. This "calorimetric" estimate has advantage of being practically free from systematic shower model uncertainties. The primary identification is inferred from the position of the shower maximum, Xmax, in the longitudinal shower profile, the heavier primaries yielding earlier development corresponding to smaller Xmax values (measured from the top of the atmosphere).

Each of the FD pixels views the light emitted from a given direction in the sky. Thus, the directions of the set of pixels viewing the shower define a plane, the Shower Detector Plane (SDP). The time information of the pixels is used for the reconstruction of the shower axis in the SDP plane. For a given geometry, the arrival time of light at the pixel i is given by the following expression

$$t_i = t_0 + \frac{R_p}{c} tan[(\chi_0 - \chi_i)/2], \tag{1}$$

where c is the speed of light. Notice that the above expression contains three unknown parameters, t_0 , R_p and χ_0 as illustrated in fig. 7.

The uncertainty of the three parameters depends on the particular geometry and on the observed track length. One possibility to improuve the reconstruction accuracy is to perform stereo observations. With all FD sites in operation, the Pierre Auger Observatory will achieve full efficiency for

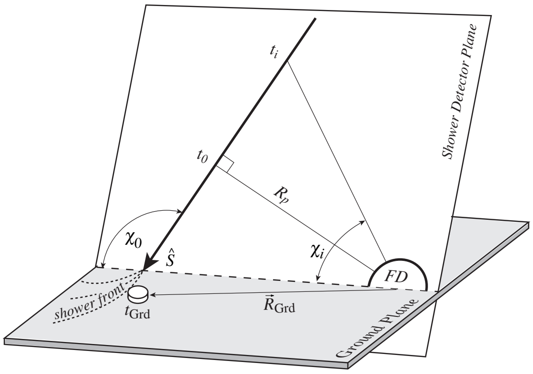

Figure 7: Geometrical shower construction from the FD observables.

stereo observation at energies above 2 10^{19} eV. Another very effective reduction of the fit parameters can be obtained by combining the information from the Surface Detector with that of the telescopes [14]. In this so called hybrid reconstruction the time t_0 at which the shower front reaches the position of closest approach to the telescope, is related to the ground array tank time t_{GND}, its position $\vec{R}_{GND}$ and the shower direction unit vector $\hat{S}$ by the equation:

$$t_0 = t_{GND} - (\vec{R}_{GND} \cdot \hat{S})/c. \tag{2}$$

Since the SD operates at a 100% duty cycle, most of the events observed by FD are hybrid.

In the hybrid analysis a accurate synchronization of the telescopes and the ground array is important. A direct measurement of the SD/FD synchronization is provided by the CLF. Part of the laser pulse is picked off by an optical fiber and injected immediately into a tank placed next to the laser facility for this purpose. The tank's measurement of the pulse emission time can then be compared with the FD determination of the same pulse emission time. The CLF is firing periodically during data taking, which allows the SD/FD timing to be monitored. The hybrid reconstruction was checked by using laser events generated by the CLF. The shower axis was determined both by observing in mono-mode with a telescope located at 26 km from the CLF and by a single tank hybrid mode. The accuracy of the reconstructed location of the CLF increased from 550 m to 20 m when using the time information from the surface station, demonstrating the power of the hybrid reconstruction.

Once the shower geometry has been determined, the primary energy is estimated. The FD profile reconstruction procedure uses as input the cali-

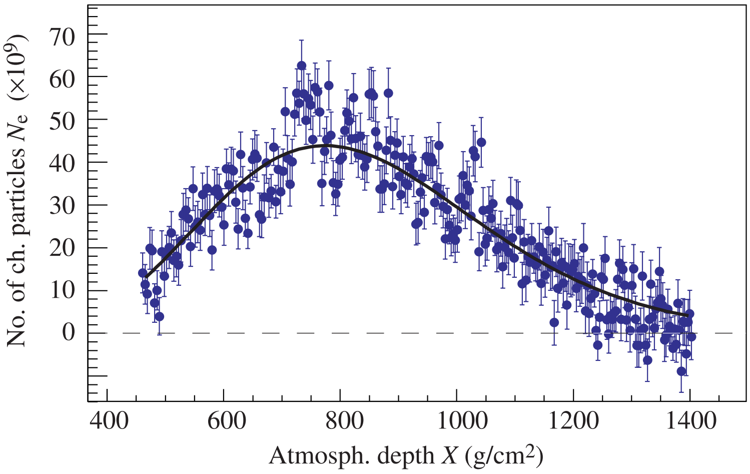

Figure 8: Longitudinal shower profile. The line represents the Gaisser-Hillas fit.

brated FADC traces, the reconstructed geometry of the shower axis and a model of aerosol scattering in the atmosphere. The geometry of the shower and the atmospheric scattering model are used to transform the light received at the detector to the light emitted from the shower axis as a function of slant depth (in g/cm^2). The fluorescence light emitted from a volume of air is proportional to the energy dissipated by the shower particles in that volume. The integral of the light signal is thus proportional to the shower energy. The reconstructed longitudinal profile of a hybrid event is shown in fig. 8. The solid line corresponds to a Gaisser-Hillas function [15] yielding the primary energy. The energy obtained for the event is in agreement with the S(1000) determination from the SD data.

Several hundreds of events with energy estimated to above 10^{19} eV have been collected with the Surface Detector. Around March - April 2005, half of the total detector array should be operational with an integrated exposure (since the beginning of the experiment) close to the exposure of AGASA. Scaling from the present yield, about 3000 events/year above 10^{19} eV are expected for the full array. Several hundreds of good quality hybrid events have also been collected so far and the preliminary analysis of the hybrid data show consistency between the energy estimates of the Fluorescence and Surface Detector.

6 Conclusion

The construction of the southern site of the Pierre Auger Observatory is well in progress on the Pampa in Argentina. More than 600 out of 1600 Surface Detector stations and two of the four Fluorescence Detector sites are currently in operation. A steady data taking started in January 2004. The performance is excellent, in many aspects better than original specifications. Several hundreds of events with energies above 10^{19} eV have been detected with the ground array and the preliminary analysis of the hybrid data shows consistency between energy estimates obtained from the two differents detectors.

In the near future, the data from the Pierre Auger Observatory will allow to determine with good accuracy the highest energy part of the cosmic ray spectrum and to search for anisotropies in the arrival direction. Furthermore, the detection of very inclined showers will allow almost background free measurements of ultra-high energy neutrinos.

In parallel to the completion of the southern observatory, planned for early 2006, R&D has started for the northern observatory. Currently two sites are being considered, Utah and Colorado, and their evaluation is in progress.

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